The object of this study is the process of determining the coordinates of low-visible aerial objects. The main hypothesis of the research assumed that the signals emitted by airborne systems of airborne objects that are not visible to radar stations have a greater power than the signal reflected from the airborne object. This, in turn, could improve the signal/noise ratio and, accordingly, the accuracy of determining the coordinates of low-visible aerial objects. It is suggested to use Software-Defined Radio receivers to receive such signals emitted by on-board systems of low-visible aerial objects.

It was established that the main sources of signals for Software-Defined Radio receivers are signals of command, telemetry, target channels, manual control channels, and satellite navigation. It was established that an additional distinguishing feature when determining the coordinates of low-visible aerial objects is the uniqueness of their spectra and spectrograms.

The method of determining the coordinates of low-visible aerial objects when using Software-Defined Radio receivers has been improved, which, unlike the known ones, involves:
- the use as signals for Software-Defined Radio of signal receivers of on-board equipment of low-visible aerial objects;
- the use of a priori coordinate values of a low-visible aerial object;
- conducting additional spectral analysis of signals of on-board systems of low-visible aerial objects.

The spectra and spectrograms of signals of on-board systems of aerial objects when using non-directional and directional antennas were experimentally determined. The experimental studies confirm the possibility of using the Software-Defined Radio receiver to receive signals from airborne equipment and improve the signal-to-noise ratio.

The accuracy of determining the coordinates of aerial objects when using Software-Defined Radio receivers was evaluated. A decrease in the error of determining plane coordinates by the Software-Defined Radio system of receivers compared to the accuracy of determining coordinates by the P-19 MA radar station was established by an average of 1.88–2.47 times, depending on the distance to the aerial object.

Keywords: low-visible aerial object, Software-Defined Radio, receiver, determination of coordinates, accuracy

1. Introduction

Modern technologies make it possible to create a new cluster of aerial objects with a small effective scattering surface [1, 2]. Such aerial objects are difficult for radar stations to detect and track. In the work, a low-visible aerial object is an aerial object whose reflected signal in the direction of the radar station is weak. This, in turn, leads to a decrease in the signal-to-noise ratio and, accordingly, makes it difficult to detect and determine the coordinates of such aerial objects. Taking into account the maneuverability of low-visible aerial objects, this additionally leads to a deterioration in the accuracy of their detection [3].

Unmanned aerial vehicles are a vivid representative of low-visible aerial objects. Unmanned aerial vehicles are used for cargo transportation, security, environmental monitoring, communication, demining, reconnaissance, surveillance, as kamikaze drones, etc. [4, 5].
surface of operational-level unmanned aerial vehicles (for example, “Orlan-10”) when detected by radar stations is from 0.01 sq.m to 0.2 sq.m, depending on the wavelength range [6]. The effective dispersion surface of unmanned aerial vehicles of the tactical level (for example, “Irkut-2M”, “Zala-421”) when detected by radar stations is from 0.001 sq.m to 0.01 sq.m, depending on wavelength [7, 8].

The anti-aircraft defense of any state today will not be able to fully counter unmanned aerial vehicles [9, 10]. Surveillance two-coordinate radar stations of the P-18 type (Ukraine) and their variants do not provide detection and determination of the coordinates of unmanned aerial vehicles even at the operational level [10]. Three-coordinate radar stations have partial capabilities for detecting unmanned aerial vehicles of the operational level and do not detect unmanned aerial vehicles of the tactical level with the necessary requirements for detection indicators and accuracy of coordinate determination [10].

The main known methods of increasing the detection indicators and the accuracy of determining the coordinates of unmanned aerial vehicles are mainly aimed at the use of active radar methods. The coordinates of the aerial object are measured by known methods. These are range-finding, difference-range-finding, total-difference range-finding methods, etc. [10]. It is known that the accuracy of determining an arbitrary coordinate of a low-visible aerial object is determined by the error of its determination according to expression (1) [11]:

$$\sigma_R = \frac{\Delta R}{q},$$  \hspace{1cm} (1)

where $\sigma_R$ is the error of determining the arbitrary coordinate $R$, $\Delta R$ – resolution along the $R$ coordinate; $q$ is the signal/noise ratio.

Therefore, taking into account expression (1) [11], known methods of improving the accuracy of determining the coordinates of low-visible aerial objects are aimed at improving the resolution of the radar station and increasing the signal/noise ratio.

Improving the resolution of a radar station is aimed at reducing the width of the antenna pattern or increasing the signal-to-noise ratio. Reducing the width of the antenna’s directional pattern involves making structural changes and cannot be implemented without changing the technical characteristics of the radar station. An increase in the signal-to-noise ratio when detecting low-visible aerial objects implies an increase in the number of radar stations and an increase in their energy potential [12]. This, in turn, significantly affects the increase in the cost of creating a radar field and does not always satisfy the relevant requirements.

Therefore, finding ways to increase the signal/noise ratio when determining the coordinates of aerial objects is an urgent task. An increase in the signal/noise ratio, in turn, will lead to a decrease in the error in determining the coordinates of low-visible aerial objects.

2. Literature review and problem statement

In [13], to increase the signal/noise ratio, a method of compacting the location of radar stations is proposed. The disadvantage of [13] is a significant increase in the number of radar stations, which is difficult to implement in practice. The issue of synchronizing the operation of radar stations remained unresolved. This, in turn, does not lead to an increase in the signal-to-noise ratio.

In [14], a method of combining information from radar stations using sounding signals with different wavelengths is proposed. The disadvantage of [14] is the practical complexity of processing signals of different frequencies. Also, the issue of synchronizing the operation of radar stations of different ranges remained unresolved. This, in turn, does not lead to an increase in the signal-to-noise ratio.

In [15], the use of complex sounding signals for the detection of low-visible aerial objects is proposed. The disadvantage of [15] is the complication of algorithms for processing signals reflected from aerial objects. The question of improving the accuracy of determining the coordinates of aerial objects using complex signals remained unresolved.

In [16], the use of a network of radar stations and a method of joint processing of reflected signals are proposed. The disadvantage of [16] is the impossibility of providing a synchronous survey of the airspace when using two-coordinate survey radar stations. This, in turn, will not lead to an additive increase in the signal/noise ratio when determining the coordinates of aerial objects.

A network of two radar stations and methods of processing coherent signals from two radar stations are proposed in [17]. The disadvantage of [17] is the practical difficulty of ensuring coherent processing of signals from two radar stations. The incoherence of the processing will not make it possible to increase the signal/noise ratio and, accordingly, the accuracy of determining the coordinates of an low-visible aerial object.

In [18], the use of spectra of signals reflected from a low-visible aerial object and methods of spectral processing are proposed. The disadvantage of [18] is the mandatory availability of a priori information about the parameters of the reflected signal, which is complicated in practice. This, in turn, does not solve the issue of increasing the accuracy of determining the coordinates of an aerial object.

In [19], the use of the Hellstrom strategy and the Petrov-Galerkin transformation is proposed. The disadvantage of [19] is the mandatory availability of a priori information about the parameters of the reflected signal. Hellstrom’s strategy and the Petrov-Galerkin transformation lead to stabilization of the false alarm rate but do not allow solving the issue of increasing the signal-to-noise ratio.

In [20], the increase in the detection indicators and the accuracy of determining the coordinates of low-visible aerial objects is ensured due to the additional use of the energy of cellular communication signals. In theory, this leads to an increase in the signal-to-noise ratio. The disadvantage of [20] is the difficulty in synchronizing the operation of the radar station and cellular communication stations.

In [21], a method of joint processing of signals from two surveillance radar stations and a cellular communication station is proposed. The disadvantage of [21] is the practical difficulty of ensuring the synchronous operation of two radar stations and a cellular communication station.

In [22], the increase in the detection indicators and the accuracy of determining the coordinates of low-visible aerial objects is ensured due to the additional use of the energy of the navigation signals of space systems. An unresolved issue in [22] is the difficulty in synchronizing the operation
of the radar station and the orbital grouping of navigational spacecraft.

In [23], a method of distributed reception of signals by the main and additional reception channels of one radar station is proposed. The introduction of an additional reception channel increases the signal-to-noise ratio and, accordingly, the accuracy of determining the coordinates of an aerial object. The disadvantage of [23] is the need for structural reconstruction of the radar station. This issue remains unresolved.

In [24], a model of a radar station with an additional reception channel was proposed and the detection zone of such a radar station was calculated. The introduction of an additional reception channel increases the signal-to-noise ratio and, accordingly, the accuracy of determining the coordinates of an aerial object. Unsolved in [24] is the negative impact of the penetrating signal from an additional radiation source.

In [25], the use of additional signals from onboard transponders of aerial objects is proposed. The disadvantage of [25] is only the declaration of such a possibility without carrying out appropriate mathematical calculations. The issue of practical implementation also remains unresolved [25].

Additional use of Automatic Dependent Surveillance-Broadcast (ADS-B) receivers is proposed in [26]. Additionally, the signal received by ADS-B receivers certainly increases the detection rates and the accuracy of determining the coordinates of low-visible aerial objects. The disadvantage of [26] is the mandatory presence of appropriate ADS-B transponders on the air object. Providing each air object with such a transponder is an unresolved issue.

Paper [27] proposed methods of increasing the accuracy of determining the coordinates of aerial objects, similar to those used in the United States of America's Loran-C navigation system. The disadvantage of [27] is the practical implementation of the proposed method only in navigation tasks. The issue of using methods [27] for detecting low-visible aerial objects remains unresolved.

In [28], methods of increasing the accuracy of determining the coordinates of low-visible aerial objects due to the use of the multilateration system (MLAT) are proposed. The disadvantage of [28] is the possibility of practical implementation of the method only within the boundaries of airfields and airports. The issue of synchronization of elements of the multilateration system also remains unresolved.

Study [29] proposed methods of increasing the accuracy of determining the coordinates of low-visible aerial objects by using the Wide area Multilateration (WAM) system. The disadvantage of [29] is the large distances between the receivers of the system, which requires a significant power of reflected signals from low-visible aerial objects.

In [30], a theoretical method of maximum likelihood was proposed for estimating the navigational parameters of an aerial object. The use of the method from [30] ensures obtaining estimates of the coordinates of the aerial object, which are close to the optimal ones. The disadvantage of [30] is its only theoretical focus and the need to calculate complex multidimensional objective functions.

In [31], a theoretical method of reducing the search space for target functions is proposed. The method from [31] involves the use of only quadratic objective functions. The disadvantage of [31] is obtaining statistically shifted and statistically suboptimal theoretical estimates of the coordinates of low-visible aerial objects. The issue of improving the accuracy of determining the coordinates of a low-visible aerial object remains unresolved.

In [32], additional use of the MLAT system was proposed in the detection and determination of the coordinates of a low-visible aerial object by a radar station. The disadvantage of [32] is the mandatory presence of appropriate ADS-B transponders on the air object to ensure the operation of the MLAT system. Providing each air object with such a transponder is an unresolved issue.

In [33], a method of suppressing a penetrating signal with an additional receiving channel in a radar station is proposed. The disadvantage of [33] is the complication of constructing the reception clock of the radar station. In addition, suppressing the penetrating signal also suppresses the useful signal reflected from a low-visible aerial object.

In [34], a method of constructing a radar field using a network of radar stations based on a genetic algorithm is proposed. The disadvantage of [34] is the availability of a priori information about the flight routes of low-visible aerial objects, which in practice leads to certain difficulties. The lack of a priori information, in turn, does not ensure an increase in the signal/noise ratio and the accuracy of determining the coordinates of a low-visible aerial object.

In [35], a method of integrating sources of information on unmanned aerial vehicles is proposed. The method involves the integration of information from radar sources and from sources that receive a sound signal. The disadvantage of [35] is the lack of algorithms for processing signals from unmanned aerial vehicles after their integration. The issue of increasing the signal-to-noise ratio remains unresolved.

In [36], a method of detecting objects based on the results of sound signal analysis is proposed. The sound signal can be used as an additional source of information regarding unmanned aerial vehicles, especially the Shahed type [37]. The disadvantage of [36] is the small detection range of an unmanned aerial vehicle.

Thus, the known methods of detecting and determining the coordinates of low-visible aerial objects are mainly aimed at increasing the signal/noise ratio in the radar station itself, or due to the use of several radar stations. Known methods include:
- an increase of the energy radar station;
- an increase in the number of radar stations of the same type;
- the use of radar stations of different frequency ranges;
- the use of complex probing signals;
- combining several radar stations into multi-positional systems;

Thus, the known methods of detecting and determining the coordinates of low-visible aerial objects are:
- a low value of the signal/noise ratio when detecting low-visible aerial objects;
- low accuracy of determining the coordinates of low-visible aerial objects by the radar station;
- low secrecy of the system's operation (especially under conditions of martial law, hybrid war, or active hostilities, for example, [37]).

The experience of repelling Russia's armed aggression against Ukraine [38, 39] confirmed that the accuracy of
The main hypothesis of the research assumed that the signals emitted by airborne systems of low-visible aerial objects have a greater power than the signal reflected from the airborne object. This, in turn, will increase the signal/noise ratio and, accordingly, the accuracy of determining the coordinates of low-visible aerial objects. It is suggested to use Software-Defined Radio receivers to receive such signals emitted by on-board systems of low-visible aerial objects.

The use of SDR receivers does not mean a complete rejection of the use of radar stations for the detection of low-visible aerial objects. The SDR system of receivers should be used either as an additional source for detecting and determining the coordinates of aerial objects to the radar station, or as a separate system that issues preliminary target designations to radar devices. The use of the SDR system of receivers will reduce the time of operation of radar stations and, accordingly, ensure the stealth of operation and increase the survivability of the radar station. This is especially important in the context of modern wars and armed conflicts.

The following research methods were used during our study:
- mathematical apparatus of matrix theory;
- radar location methods;
- methods of digital signal processing;
- methods of probability theory and mathematical statistics;
- methods of system analysis;
- methods of statistical theory of detection and measurement of parameters of radar signals;
- iterative methods;
- differential calculus methods;
- methods of multi-position radar;
- methods of mathematical modeling.

During the study, the following limitations and assumptions were made:
- radar stations are limited to P-18MA (Ukraine), P-18MU (Ukraine), P-18 “Malachite” (Ukraine) radar stations;
- radio receiving devices of radar stations are digital;
- unmanned aerial vehicles are considered low-visible aerial objects;
- when determining the characteristics of the main signals emitted by on-board systems of low-visible aerial objects, the Orlan-10 is considered as an example;
- it is assumed that there are no obstacles;
- it is assumed that reception of the SDR signal by receivers is ensured;
- SDR receivers in the system work synchronously;
- the Monte Carlo statistical test method is used for modeling;
- experimental studies were conducted with a DVB-T+FM+DAB 820T2 & SDR receiver.

5. Results of research on improving the method for determining the coordinates of low-visible aerial objects

5.1. Brief analysis of the main signals emitted by on-board systems of low-visible aerial objects

The necessity of posing and solving the problem of analyzing the signals emitted by on-board systems of low-visible aerial objects is due to the proof of the possibility of using such signals to increase the signal-to-noise ratio. This, in turn, leads, according to expression (1), to an increase in the accuracy of determining the coordinates of low-visible aerial objects.

The main sources of signals for SDR receivers are the signals of the following channels of the unmanned aerial vehicle:
- command (the flight route is adjusted, the operating modes of the target equipment are changed, etc.);
Information and controlling system

– telemetric (data on flight route coordinates, on-board equipment operating modes);
– issuance of target information (signals from the on-board camera);
– satellite navigation (navigation, GPS or GLONASS signals).

The main unmasking feature of the target information delivery channel signal is its relatively large (1–10 MHz) spectrum width. This is due to the need to ensure a high speed of target information transmission. Features of other UAV channels:
– low data transfer speed;
– relatively small (0.3 MHz) spectrum width;
– the presence of carrier frequency changes in telemetry channel signals, as a rule, jump-like and periodic (pseudo-random tuning of the operating frequency (PSR)).

For example, Table 1 gives the main characteristics of signals of the telemetry channel of the Orlan-10 unmanned aerial vehicle. Information for Table 1 is compiled from [6, 42, 43].

Fig. 1 shows the spectrum and spectrogram of the telemetry channel signal of the Orlan-10 unmanned aerial vehicle as an example. Fig. 1 was obtained based on the results of the analysis [6, 42, 43]. The term “spectrogram” refers to an image that highlights the dependence of the spectral density of the signal power on time (for example, [44, 45]).

In Fig. 1, the spectrum and spectrogram were obtained under the condition of a spectrum width of 1 MHz at frequencies from 921 MHz to 922 MHz. From the analysis of Fig. 1, it can be concluded that the signal-to-noise ratio for telemetry channel signals is approximately 24 dB. It is known [6, 12–14] that when the Orlan-10 UAV is detected by radar stations of the P-18MA, P-19 MA type, the average is from 8 dB to 13 dB, depending on the detection conditions. This indicates an increase in the signal/noise ratio due to the use of on-board equipment signals of low-visible aerial objects.

For example, Table 2 gives the main characteristics of the signals of the telemetry channel of the Eleron-3SV unmanned aerial vehicle. Information for Table 2 was obtained from [46].

Fig. 2 shows the spectrum and spectrogram of the telemetry channel signal of the Eleron-3SV unmanned aerial vehicle as an example. Fig. 2 was obtained based on the results of the analysis [46].

### Table 1

<table>
<thead>
<tr>
<th>The name of the signal parameter</th>
<th>Frequency range, MHz</th>
<th>Signal spectrum width, MHz</th>
<th>Number of frequencies for FHSS</th>
<th>Number of frequency hops per second, times</th>
<th>Pitch of the grid of frequencies at which FHSS is performed</th>
<th>The structure of the accumulated signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter value</td>
<td>900–922</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>uniform</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>The name of the signal parameter</th>
<th>Frequency range, MHz</th>
<th>Signal spectrum width, MHz</th>
<th>Number of frequencies for FHSS</th>
<th>Number of frequency hops per second, times</th>
<th>Pitch of the grid of frequencies at which FHSS is performed</th>
<th>The structure of the accumulated signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter value</td>
<td>915–920</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>0.29</td>
<td>not uniform</td>
</tr>
</tbody>
</table>

Fig. 1. Spectrum and spectrogram spectrogram of the telemetry channel signal of the Orlan-10 unmanned aerial vehicle [6, 42, 43]
In Fig. 2, the spectrum and spectrogram were obtained under the condition of using 10 frequencies in the band from 915 MHz to 920 MHz. From the analysis of Fig. 2, it can be concluded that the signal-to-noise ratio for telemetry channel signals is approximately 17 dB. It is known [8, 12–14] that when the Eleron-3SV unmanned aerial vehicle is detected by radar stations of the P-18 MA, P-19MA type, it averages from 6 dB to 12 dB, depending on the detection conditions. This indicates an increase in the signal/noise ratio due to the use of on-board equipment signals of low-visible aerial objects.

Therefore, the above signals from the on-board equipment of unmanned aerial vehicles can be the main sources of signals for SDR receivers. Analysis of Tables 1, 2 reveals the difference in spectra and spectrograms of various unmanned aerial vehicles, which can be an additional distinguishing feature when determining the coordinates of unmanned aerial vehicles.

5.2. The main stages of the method for determining the coordinates of stealth air objects

A system of three SDR receivers was considered (Fig. 3). This is the minimum required number of SDR receivers for determining the coordinates of an aerial object using the passive difference-range-finding method (for example, [11, 13, 22, 31]). The number of receivers in operation is not optimized in the work: this is the subject of further research. Each SDR receiver receives signals from the aircraft’s on-board systems.

...
receiver. This makes it possible to denote the distance difference by the symbol \( \Delta R_i \) instead of the symbol \( \Delta R_j(\alpha, \beta) \). It also takes into account the well-known fact that the number of independent differences in the moments of arrival of signals on-board systems is equal to \((N-1)\).

From the analysis of expression (3) it follows that four quantities are unknown, namely:

- coordinates of a low-visible aerial object \( x_{AO}, y_{AO}, z_{AO} \) (three unknowns);
- the unknown distance difference \( \Delta R_{in} = \Delta R_i - \Delta R_j \), which is caused by the asynchrony of the timescales of the SDR receivers.

The above does not allow solving the system of non-linear equations (expression (3)) by analytical methods. Therefore, hereafter, we shall use iterative methods to determine the coordinates of a low-visible aerial object. Such methods have proven efficient in the application of swarm optimization methods, for example, [49, 50].

The main stages of the method for determining the coordinates of low-visible aerial objects when using SDR receivers are shown in Fig. 4.

The main stages of the method for determining the coordinates of low-visible aerial objects when using SDR receivers:

1. Input of initial data: the number of SDR receivers; coordinates of SDR receivers \( x_i, y_i, z_i \); a priori values of the coordinates of a low-visible aerial object \( x_{AO(0)}, y_{AO(0)}, z_{AO(0)} \) (initial approximations).
2. Calculation of the range to an aerial object from the \( i \)-th SDR receiver (expression (4)):

\[
R_i = \sqrt{(x_i - x_{AO(0)})^2 + (y_i - y_{AO(0)})^2 + (z_i - z_{AO(0)})^2}.
\]

3. Calculation of the vector of discontinuities \( C \) at the \( S \)-th iteration (expression (5)):

\[
C_{(S-1)} = (R_{(S-1)} - R_{S-1} - (T_i - T))c;
\]

\[
i = 1, \ldots, (S-1),
\]

where the symbols \( R_{(S-1)} \), \( R_{S-1} \) denote the distances from the \( i \)-th and 0-th SDR receiver to the point with coordinates \( x_{AO(0)}, y_{AO(0)}, z_{AO(0)} \). The distances \( R_{(S-1)} \) and \( R_{S-1} \) are calculated for each of the \((S-1)\) iterations; the difference \( (T_i - T) \) means the difference in the reception time of the \( i \)-th and 0-th SDR signals by the receiver; \( c \) is the speed of light.

4. Calculation of the matrix of partial derivatives \( A_S \) according to expression (6):

\[
A_{3(S)} = \frac{\partial R_i(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})}{\partial x_{AO(S)}},
\]

\[
A_{3(S)} = \frac{\partial R_i(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})}{\partial y_{AO(S)}},
\]

\[
A_{3(S)} = \frac{\partial R_i(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})}{\partial z_{AO(S)}}.
\]

5. Definition of corrective correction \( \zeta_S \) (expression (7)):

\[
\zeta_S = \left( (A_{3(S)})^T R A_{3(S)} \right)^{-1} (A_{3(S)})^T RC.
\]

6. Clarification of the coordinate vector of a stealth air object \( (x_{AO(S)}, y_{AO(S)}, z_{AO(S)}) \) (expression (8)):

\[
(\alpha_S(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})) - \alpha_S(x_{AO(S-1)}, y_{AO(S-1)}, z_{AO(S-1)}) + \zeta_S.
\]

7. Checking the conditions \((\zeta_S > P)\) or \((\zeta_S < P)\). If \((\zeta_S < P)\), the iterative process ends, \( (\alpha_S(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})) \) is taken as the estimate of the coordinates of the low-visible aerial object. If \((\zeta_S > P)\), the iterative process continues.

8. Conducting an additional spectral analysis of the signals of on-board systems of a low-visible aerial object. Such an analysis is carried out in order to determine the type of low-visible aerial object based on the data of the spectral analysis of the signals of its on-board equipment. To this end, for example, the data from Tables 1, 2 can be used, as well as Fig. 1, 2, etc. It is the use of spectral analysis and spectrograms of signals that, in addition to increasing the accuracy of coordinate determination, allows us to determine the type of low-visible aerial object.
Thus, in contrast to known methods, the improved method for determining the coordinates of low-visible aerial objects when using SDR receivers implies:
– the use as signals for SDR of signal receivers of onboard equipment of low-visible aerial objects;
– the use of a priori values of the coordinates of a low-visible aerial object \( x_{AO}(0), y_{AO}(0), z_{AO}(0) \);
– conducting additional spectral analysis of signals of onboard systems of low-visible aerial objects.

The SDR system of receivers can be used as a separate source of information about the coordinates of a low-visible aerial object, or as an additional source of information about the coordinates of a low-visible aerial object to the main radar station.

5.3. Experimental studies on the possibility of receiving signals by the SDR receiver

We shall conduct experimental studies to confirm the practical possibility of receiving SDR signals by the receiver of onboard systems of aerial objects. Initial data for conducting experimental studies:
– the place of experimental research is the city of Kharkiv (Ukraine);
– the DVB-T+FM+DAB 820T2 & SDR receiver was chosen as the SDR receiver (Fig. 5). The characteristics and parameters of the receiver are as follows [27].

Technical characteristics of the receiver:
– frequency range: 24–1900 MHz;
– sensitivity: 220 mV;
– dynamic range: 50db;
– bandwidth: 0.25–3 MHz;
– bit rate of analog-digital converter: 8 bits;
– interface: USB 2.0;
– the software AIRSPY (USA) [51] was chosen as the software when working with the SDR receiver;
– as a directional antenna, a director antenna [52] with characteristics and parameters is chosen:
  – number of elements, 5;
  – antenna length, 0.238 m;
  – coefficient of directional action, 8.56;
  – the width of the directional diagram is 92°.

Experimental installation using a non-directional antenna is shown in Fig. 6.

The spectrum and spectrogram of the received signal when using a non-directional antenna are shown in Fig. 7.
Taking into account the information from Fig. 7, it can be assumed that this is an ADS-B signal of a Russian aerial object (civilian or military). A more detailed analysis and determination of the type of aerial object can be carried out using the results of [26, 27] but this is beyond the scope of this work.

The experimental setup using a directional antenna is shown in Fig. 8.

Thus, our experimental studies confirm the possibility of using the SDR receiver to receive signals from the on-board equipment of aerial objects. A more detailed analysis and determination of the type of aerial object can be carried out using the results of [26, 27] but this is beyond the scope of this work and is the subject of further research.

5.4. Evaluation of the accuracy of determining the coordinates of air objects when using SDR receivers

We shall assess the accuracy of determining the coordinates of aerial objects by means of mathematical modeling using Monte Carlo statistical tests. At the same time, we shall use the results of [33].

Three identical SDR receivers were used, one of which is the reference, and the other two are located at a distance of 5 km from the reference. The error of the unit measurement of the plane coordinates of the aerial object along the X and Y axes is the same and is 30 m. Fig. 10 shows an assessment of the accuracy of determining the plane coordinates of an aerial object by the method of Monte Carlo statistical tests. The mean square error of determining the plane coordinates of an aerial object was chosen as an indicator of the accuracy of determining the plane coordinates.

To carry out a comparative assessment of the accuracy of determining the coordinates of an aerial object, we shall conduct a simulation of determining the coordinates of an aerial object by a single-position radar station. The radar station P-19MA (Ukraine) was considered [53]. The root mean square error of a single measurement for the P-19MA radar station is 250 m [53]. To measure the coordinates of an aerial object in the P-19MA radar station, the angular-range-measuring method is used [53]. The results of the assessment of the plane coordinates of the aerial object by the P-19MA radar station are shown in Fig. 11.

The MATLAB application package, version R2017b, was used to assess the accuracy of determining plane coordinates (Fig. 10, 11).
The main stages of the method for determining the coordinates of low-visible aerial objects:

2. Additional use of SDR transceiver HackRf One [54].
3. Use as reference ADS-B signals from aerial objects with known coordinates.

This method of synchronizing SDR receivers is discussed in more detail below for an example. It involves the following sequence of actions:

- reception of messages (signals) from aerial objects equipped with ADS-B equipment;
- attaching the timevalues of each SDR receiver to each message of the ADS-B equipment;
- data transfer to the information processing point (one of the receivers can act as a processing point);
- calculation of the difference in signal arrival time according to ADS-B data and the difference in signal arrival time according to SDR receiver data;
- calculation of timecorrection;
- adjustment (synchronization) of SDR receivers taking into account the timecorrection for each of them.

6. Discussion of results of improving the method for determining the coordinates of stealth air objects

A concise analysis of the main signals emitted by airborne systems of low-visible aerial objects has been carried out. Our analysis has made it possible to substantiate the possibility of using such signals to increase the signal/noise ratio due to the use of the SDR receiver system. It is the SDR receivers that are the consumers of the signals of on-board systems of low-visible aerial objects. This, in turn, leads, according to expression (1), to an increase in the accuracy of determining the coordinates of low-visible aerial objects.

It was established that the main sources of signals for SDR receivers are signals of command, telemetry, target channels, manual control channels and satellite navigation. Examples of the main characteristics of signals of the telemetry channel of unmanned aerial vehicles “Orlan-10” and “Eleron” are given in Tables 1, 2. Examples of spectra and spectrograms of the signals of the telemetry channel of the Orlan-10 and Eleron unmanned aerial vehicles are shown in Fig. 1, 2. From the analysis of Fig. 1, 2, it can be concluded that the signal-to-noise ratio for telemetry channel signals ranges from 17 dB to 24 dB, depending on the type of unmanned aerial vehicle. When unmanned aerial vehicles are detected by radar stations of the P-18MA, P-19 MA type, the signal-to-noise ratio ranges from 6 dB to 13 dB on average, depending on the type of aircraft and detection conditions. This indicates an increase in the signal/noise ratio due to the use of on-board equipment signals of low-visible aerial objects.

In contrast to known results, for example, [22, 23], it is proposed to use the signals of on-board equipment of unmanned aerial vehicles as the main sources of signals for SDR receivers. Analysis of Tables 1, 2 reveals the difference in the spectra and spectrograms of different UAVs, which can be an additional distinguishing feature of UAVs.

The use of SDR receivers does not mean a complete rejection of the use of radar stations for the detection of low-visible aerial objects. The SDR system of receivers should be used either as an additional source for detecting and determining the coordinates of aerial objects to the radar station, or as a separate system that issues preliminary target designations to radar devices. The use of the SDR system of receivers will reduce the time of operation of radar stations and, accordingly, ensure the stealth of operation and increase the survivability of the radar station. This is especially important in the context of modern wars and armed conflicts.

The main stages of the method for determining the coordinates of low-visible aerial objects when using SDR receivers are given in Fig. 4. The method for determining the coordinates of low-visible aerial objects when using SDR receivers has been improved, which, unlike the known ones, provides for the following:

- the use as signals for SDR of signal receivers of on-board equipment of low-visible aerial objects;
The study was conducted without financial support.
References


7. Russia behind the UAV technology curve (2021). Available at: https://issuu.com/edrmag/docs/edr_58_-_web/s/12783061


28. LORAN-C. Available at: https://skybrary.aero/articles/loran-e

29. Multilateration (MLAT) Concept of Use. Available at: https://www.icao.int/APAC/Documents/edocs/mlat_concept.pdf

Information and controlling system


37. SHAHED-136 Loitering munition / Kamikaze-Suicide drone – Iran (2023). Available at: https://www.armyrecognition.com/iran_unmanned_ground_aerial_vehicles_systems/shahed-136_loitering_munition_kamikaze-suicide_drone_iran_data.html#google_vignette

38. How drones are conquering the battlefield in Ukraine’s war (2023). Available at: https://www.euronews.com/2023/06/06/how-drones-are-conquering-the-battlefield-in-ukraines-war


43. Swiss Components For Cars and Electric Bicycles Were Found in russian Orlan-10 UAVs and Missiles (2023). Available at: https://en.defence-ua.com/industries/swiss_components_for_cars_and_electric_bicycles_were_found_in_russian_orlan_10_uavs_and_missiles-6267.html

44. What is a Spectrogram? Available at: https://vibrationresearch.com/blog/what-is-a-spectrogram

45. What is a Spectrogram? Available at: https://pnsn.org/spectrograms/what-is-a-spectrogram

46. Eleron-3SV. Available at: https://robotrends.ru/robopedia/eleron-3sv


51. AIRSPY. Available at: https://airspy.com


54. HackRF One SDR-transiver (1 MHz – 6 HHZ) maksymalna komplektatsiya. Available at: https://radioscan.com.ua/ua/p1878031526-hackrf-one-sdr.html